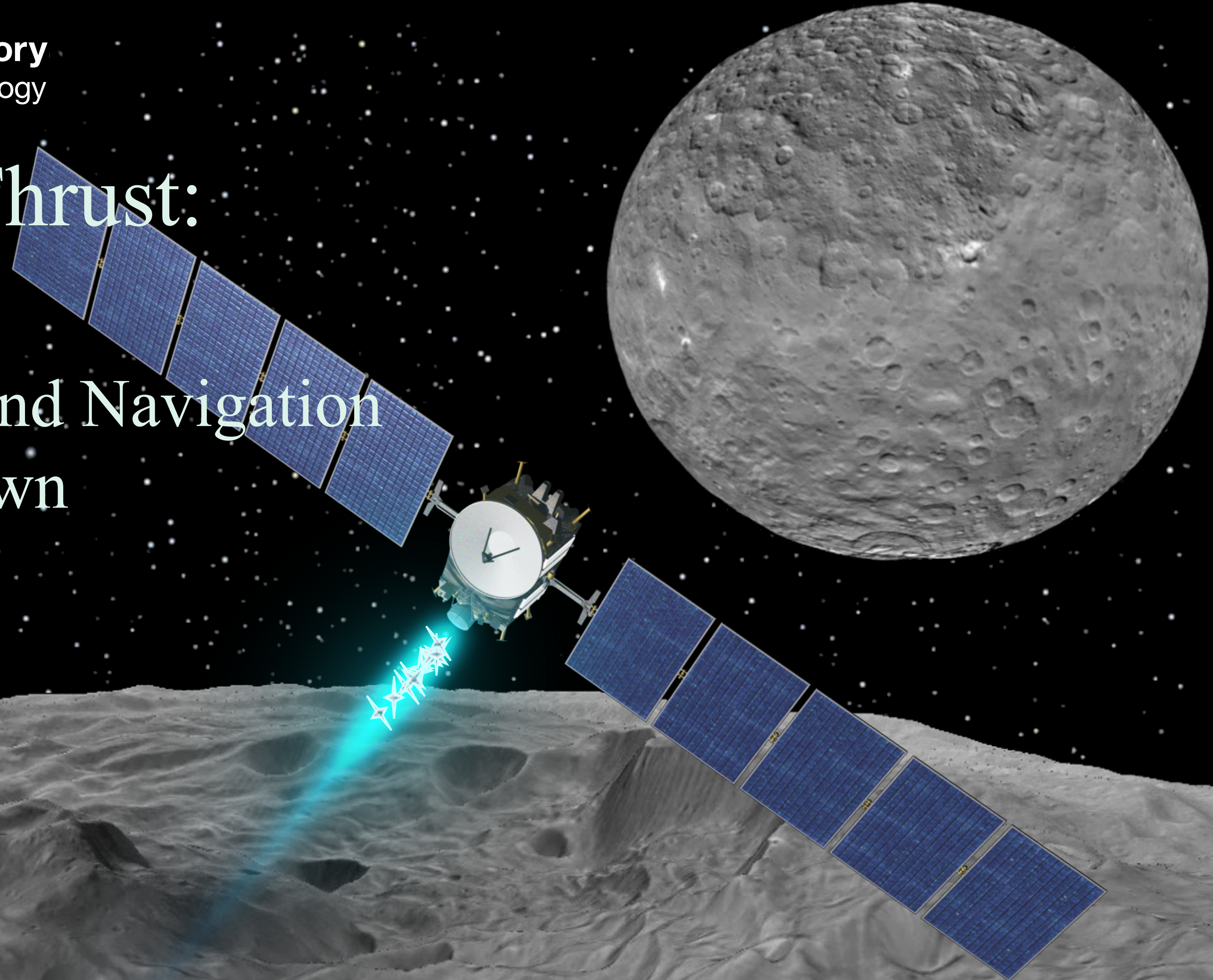
Jet Propulsion Laboratory
California Institute of Technology

Flying Low Thrust:

Mission Design and Navigation Lessons from Dawn



Don Han

ESOC Seminar

January 18, 2018

Chart Credit to Marc Rayman

Agenda

- Introduction
  - Low thrust, Dawn mission, Mission Timeline
- Dawn Spacecraft
  - IPS, Thrust Vector Control
- Dawn Mission Design
  - Optimization strategy, Missed Thrust
- Dawn Mission Planning
  - Sequencing strategy during cruise, Coasting time management, Tracking schedule (HGA, LGA, Thrust verification)
- Dawn Orbit Determination
  - Basic strategy, IPS thrusting models, IPS engine calibration, Tracking data type and schedule, OD prediction over thrusting (difficulty)
- Dawn Reference papers

- Disclaimer:
  - *Large part of this is from my internal Navigating Low Thrust Mission presentation and not updated*
  - *Mixed usage of Low Thrust, EP/SEP/IPS in this presentation*
  - *Mixed usage of MD,MD/Nav, Nav & FD*

Why Low Thrust ?

Dawn

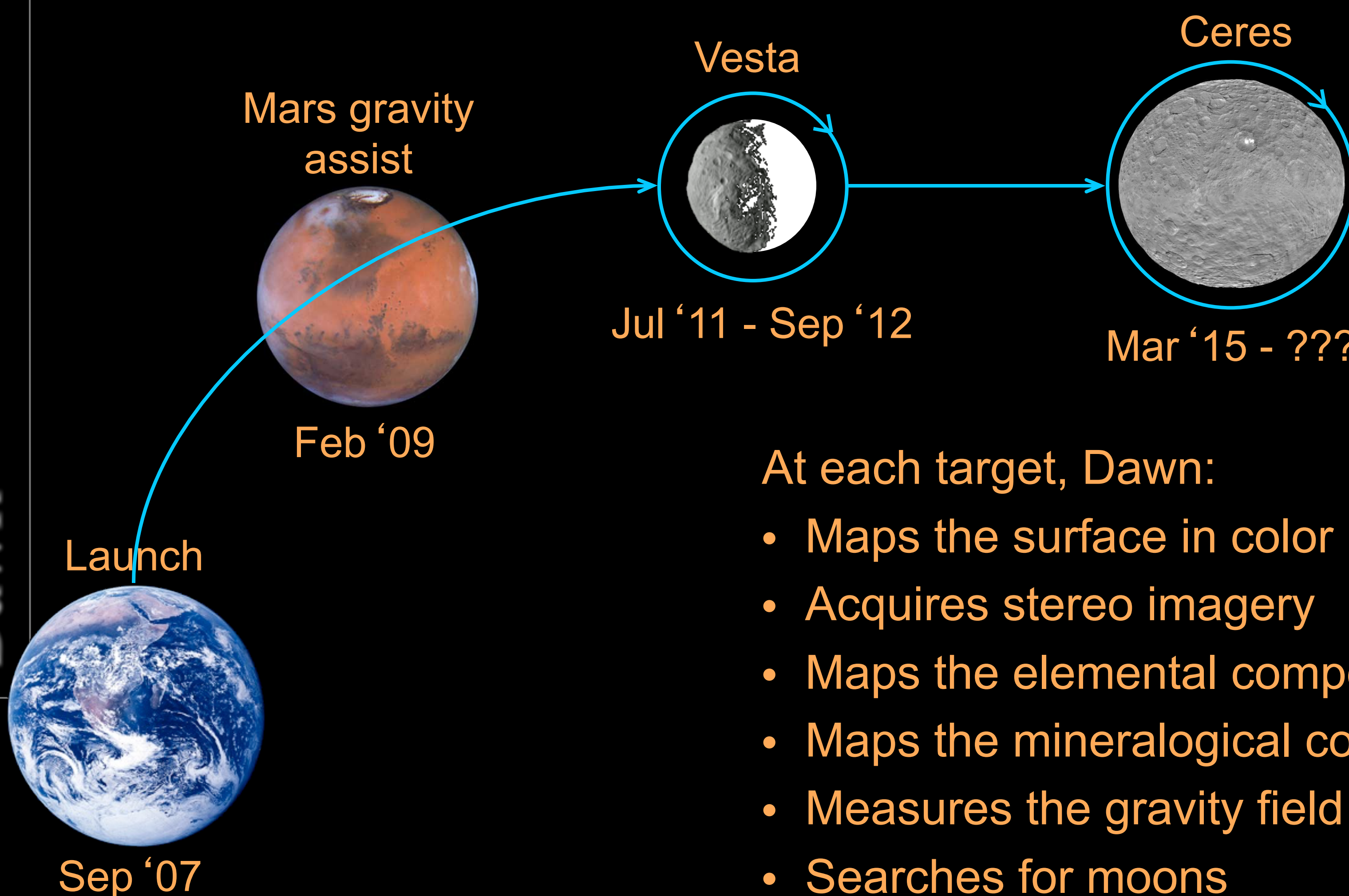
Benefits

- Enables missions that would be unaffordable or impossible with chemical propulsion.
- Highly efficient thrust
- Flexibility in mission
  - Larger launch period/window
  - Easier changes of mission in flight
- Smaller launch vehicle
  - S/C can carry a lot of Delta-V
- Critical events are rare during entire mission.

Challenges

- Higher cost S/C
  - Larger SA, more expensive propulsion, power system
- Flexibility in mission
  - Higher uncertainty in mission timeline
  - Choosing one from many solutions is often challenging.
- Complex operations
  - Many new procedures for flight team and Nav team
- Expensive operations
  - All thrusting events are important

Mission Itinerary



At each target, Dawn:

- Maps the surface in color
- Acquires stereo imagery
- Maps the elemental composition
- Maps the mineralogical composition
- Measures the gravity field
- Searches for moons

Spacecraft Propulsive ΔV (km/sec)

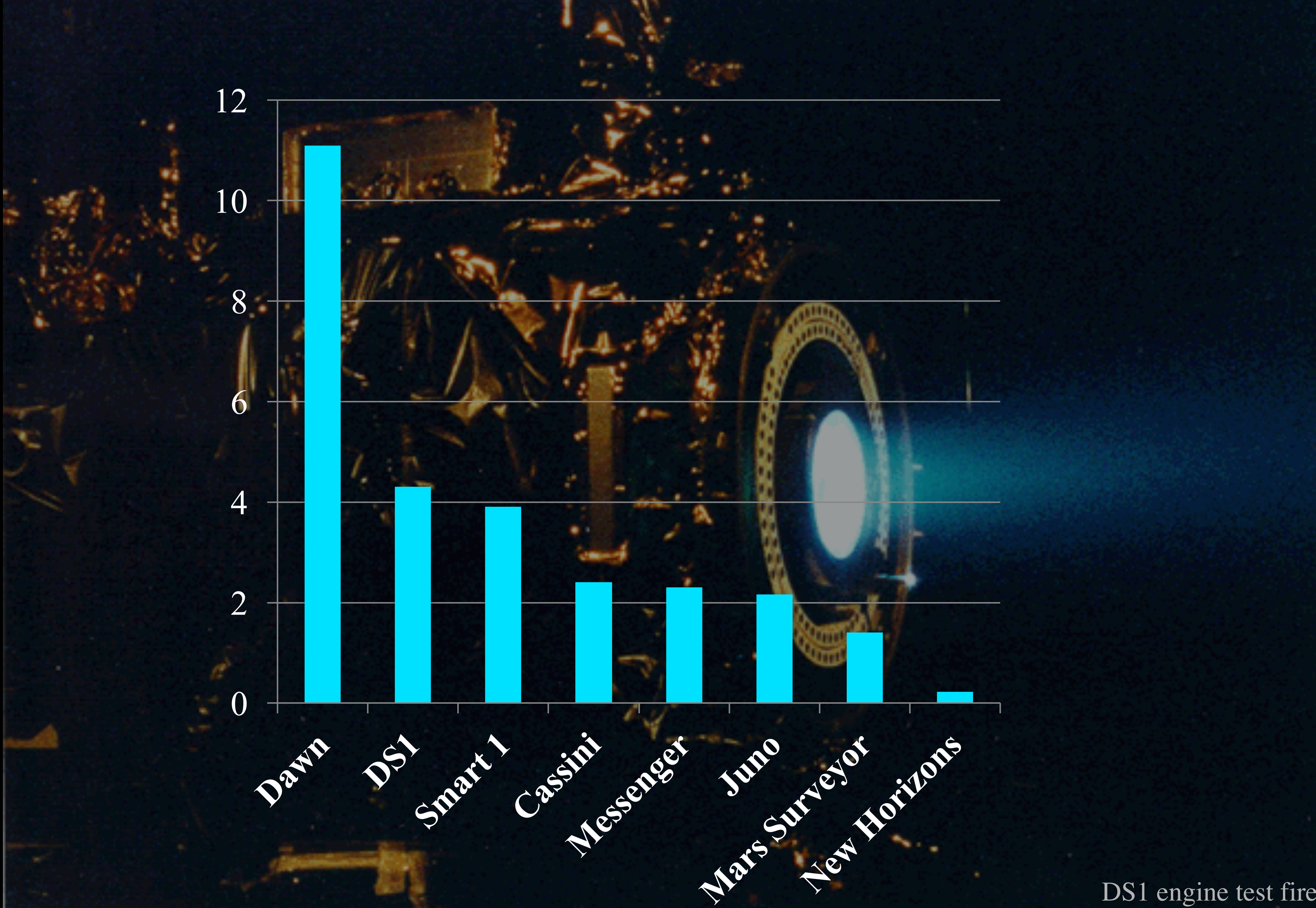
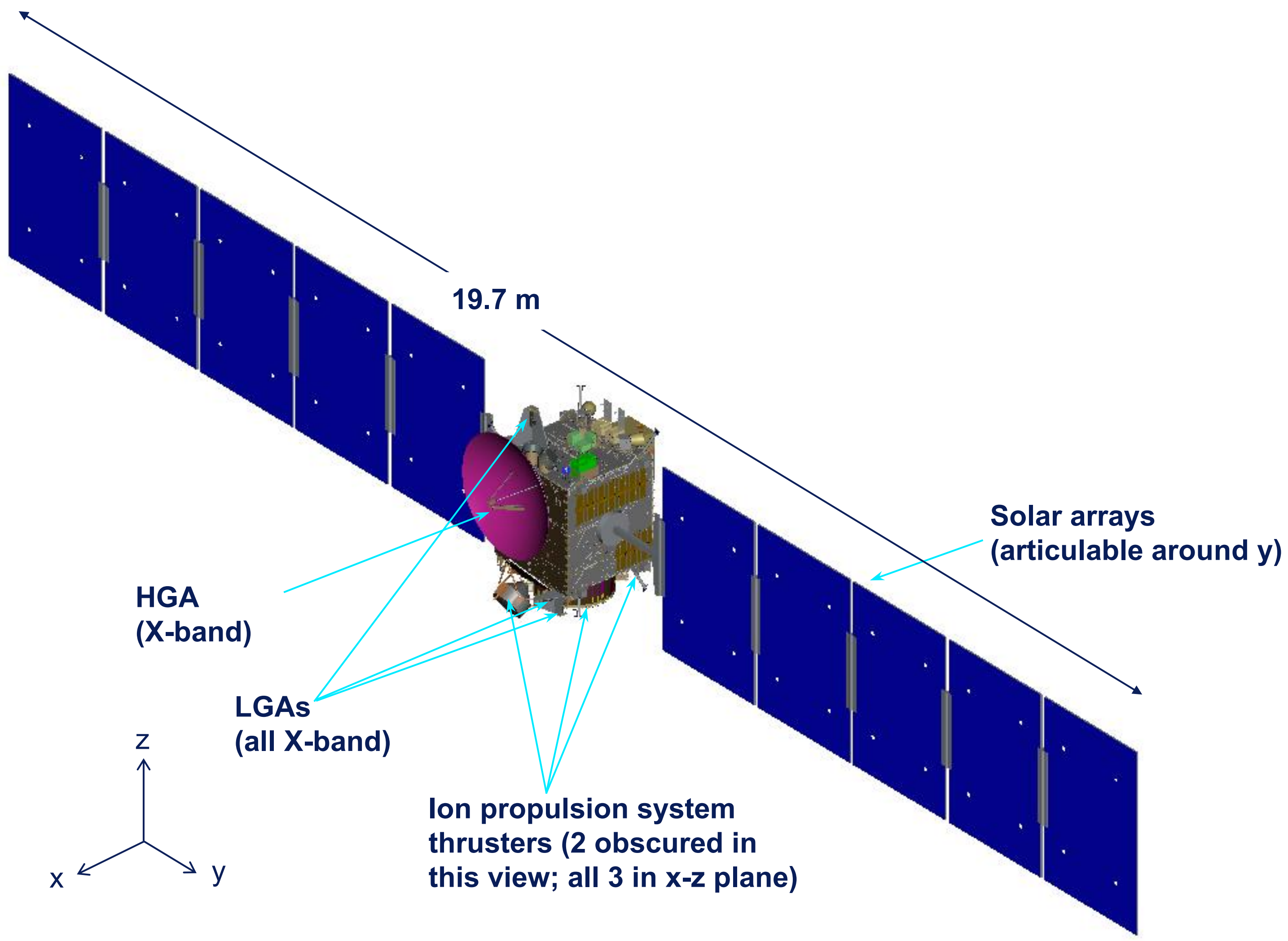


Chart Credit to Greg Whiffen

DS1 engine test fire
JPL/NASA

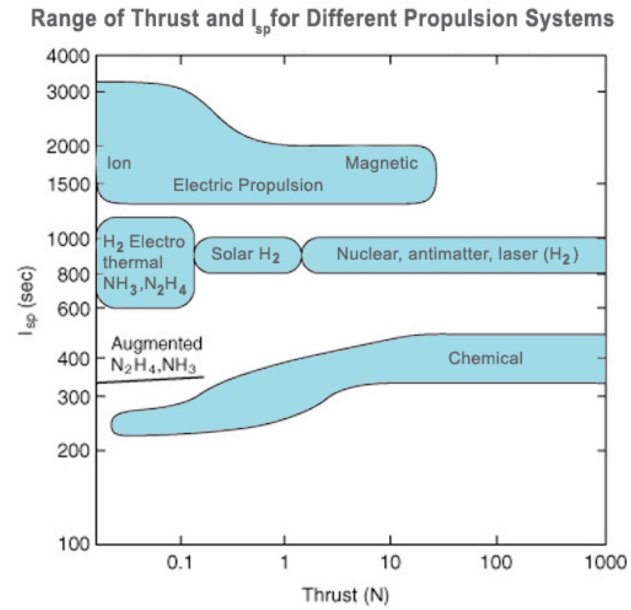
Dawn Flight System Configuration

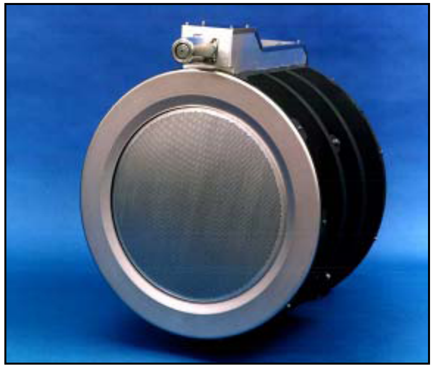


Electric Propulsion Enables Dawn

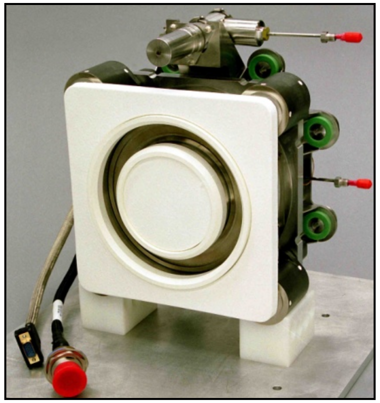
- Dawn's wet mass = 1218 kg with 425 kg of Xe

- Dawn's wet mass using chemical engine for a Vesta-only mission would be 2500 kg and require a Delta IV launch vehicle.

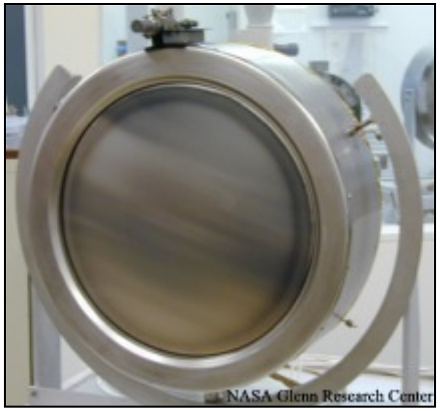




Dawn Ion Engine



Hall Thruster



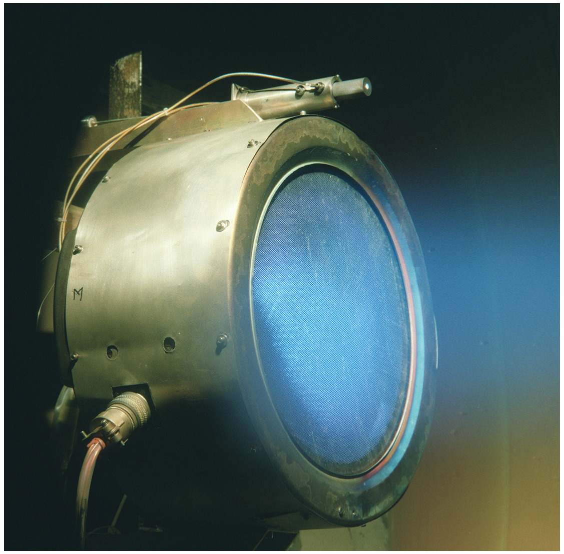
NEXT Ion Engine

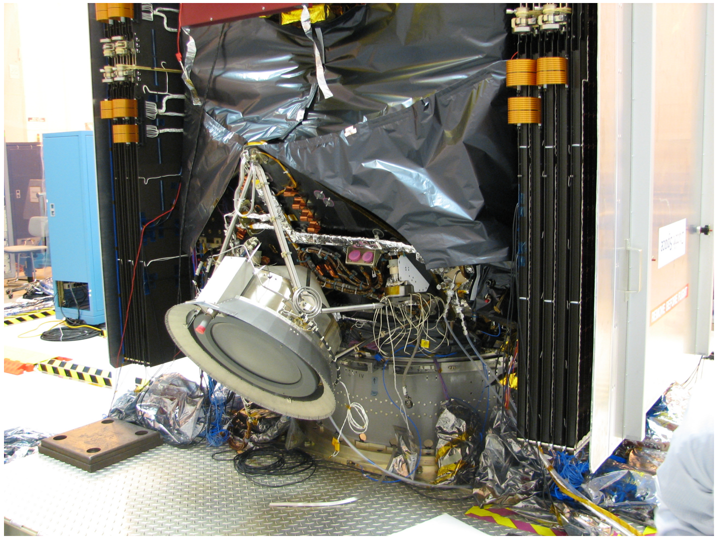
Chart Credit to Chuck Garner

Dawn

Dawn's Ion Propulsion System

- Inherited mostly from Deep Space 1.
- IPS ΔV = 11.1 km/s = Delta 7925H ΔV
- IPS has been on for 49,000 hours (5.6 years).
- The IPS has been used for **all** nominal post-launch trajectory control.
- Maximum thrust 91.6 mN,
  - 76 – 46 mN at Vesta,
  - 25 – 18 mN at Ceres
- Overall duty cycle since launch = 62%
- I_{sp}: 1740 s to 3060 s
- Input Power: 0.4 kW to 2.5 kW



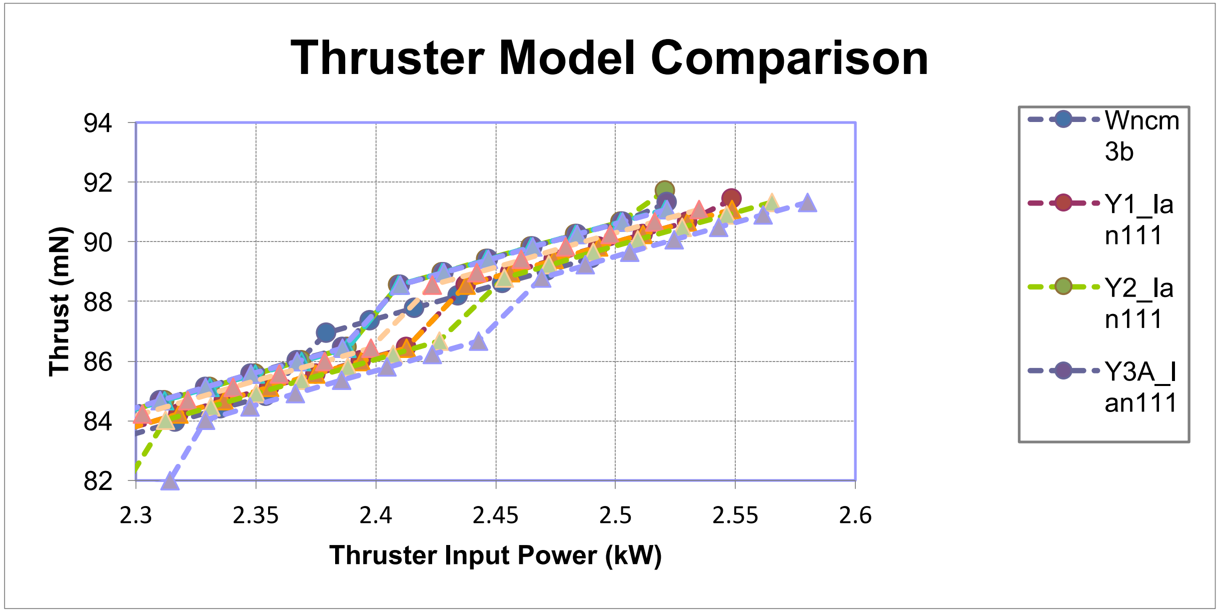


Dawn

Throttle Table

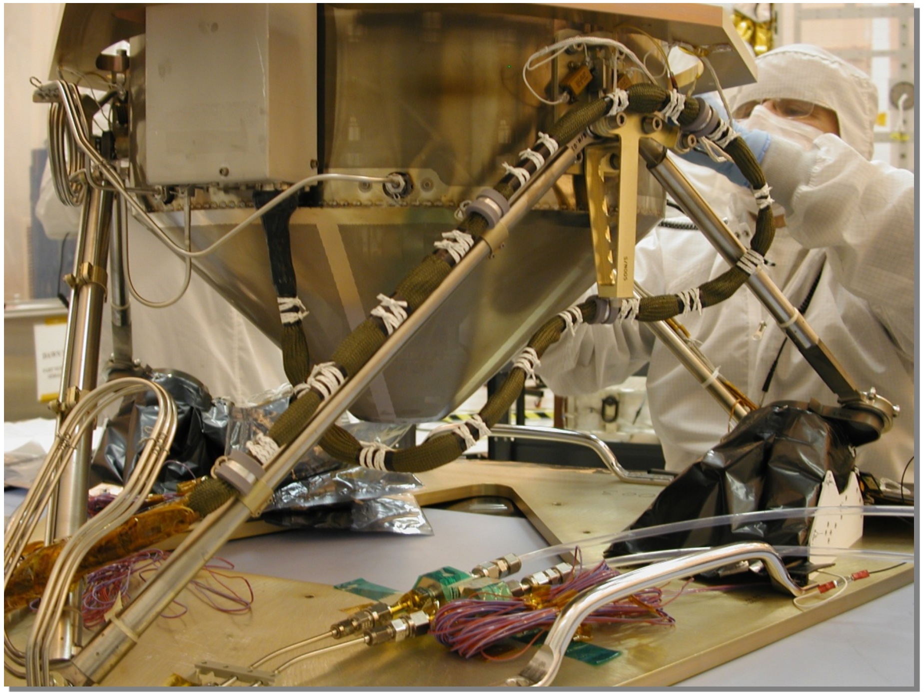
- Table includes, for all mission levels (0 to 111 for Dawn):
  - Thrust (mN),
  - PPU input power (W),
  - Mass Flow rate
  - *Throttle levels are discrete, complicating numerical optimization.*

- Many ***variations*** of throttle tables provided by spacecraft team



Thrust Vector Control (IPS)

- Typically uses gimbal to align thrust vector to S/C center of mass.
- Dawn's Thrust Gimbal Assembly (TGA)
  - Provides 2-axis control of the thrust vector
  - Dynamic range +/- 8 deg in one axis, +/- 12 deg in another
  - Anomaly detected in TGA for center thruster during Ceres orbit transfer. Center thruster was removed from nominal operation since then.



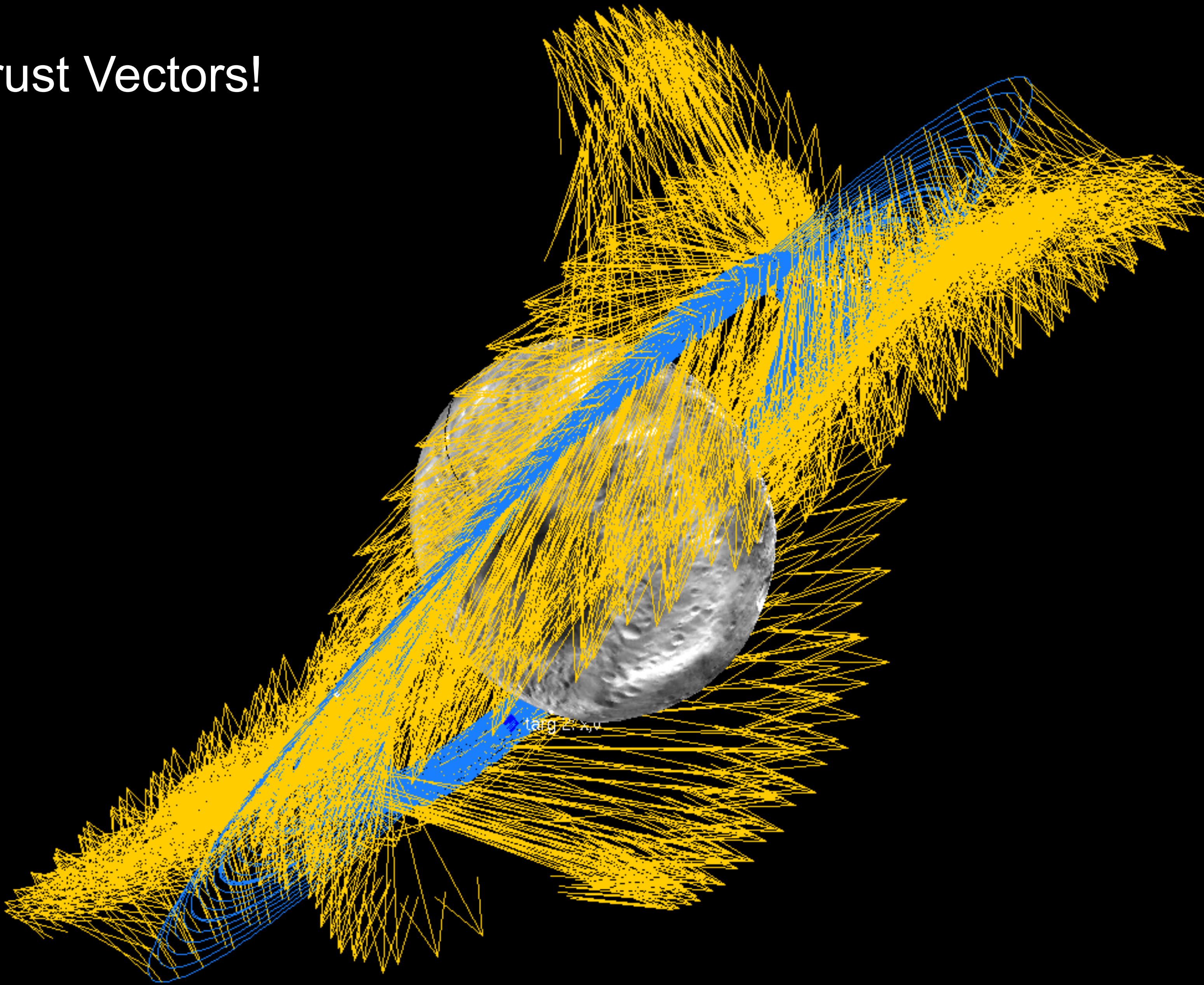
Thrust Vector Control

- Thrust vector is key product of maneuver & mission design. During cruise, it is mostly in fixed direction but often **time varying** during orbit transfers.
  - During thrusting, IPS is the only way to change the thrust direction for Dawn.
    - (Dawn uses gimbal + IPS to apply torque in 2 axes, use RWA/RCS for the other axis)

- Dawn Nav team provided updated thruster vector alignment by thrust pointing estimation.
  - Aim vector (phi, theta) for each thruster
  - Theta changes are mainly due to center of mass changes from fuel depletion.

Dawn

Thrust Vectors!



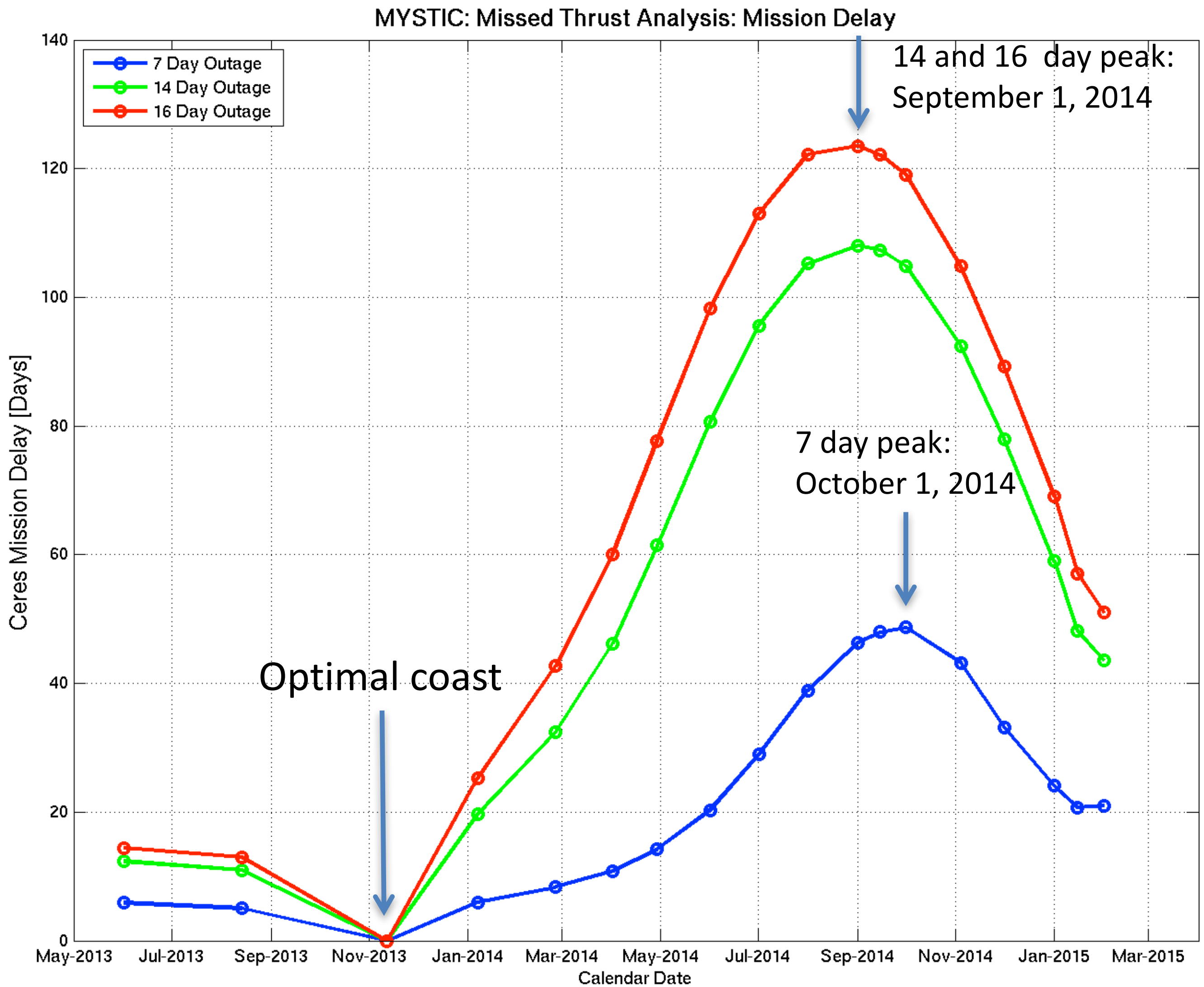
Mission Design Strategy

- For every sequence build, optimize the entire remaining reference orbit instead of going back to original reference orbit.
- Cost function is usually minimum time, but can be set to different goal. Arrival time is flexible and remains open until the approach phase.
- For Mars Gravity Assist (MGA), Trajectory Control Maneuver (TCM) was NOT designed for specific target at Mars, but hybrid goal of overall mission performance, nominal fly-by altitude (500 km), and a weak penalty for excessively long TCM durations.

Missed Thrust

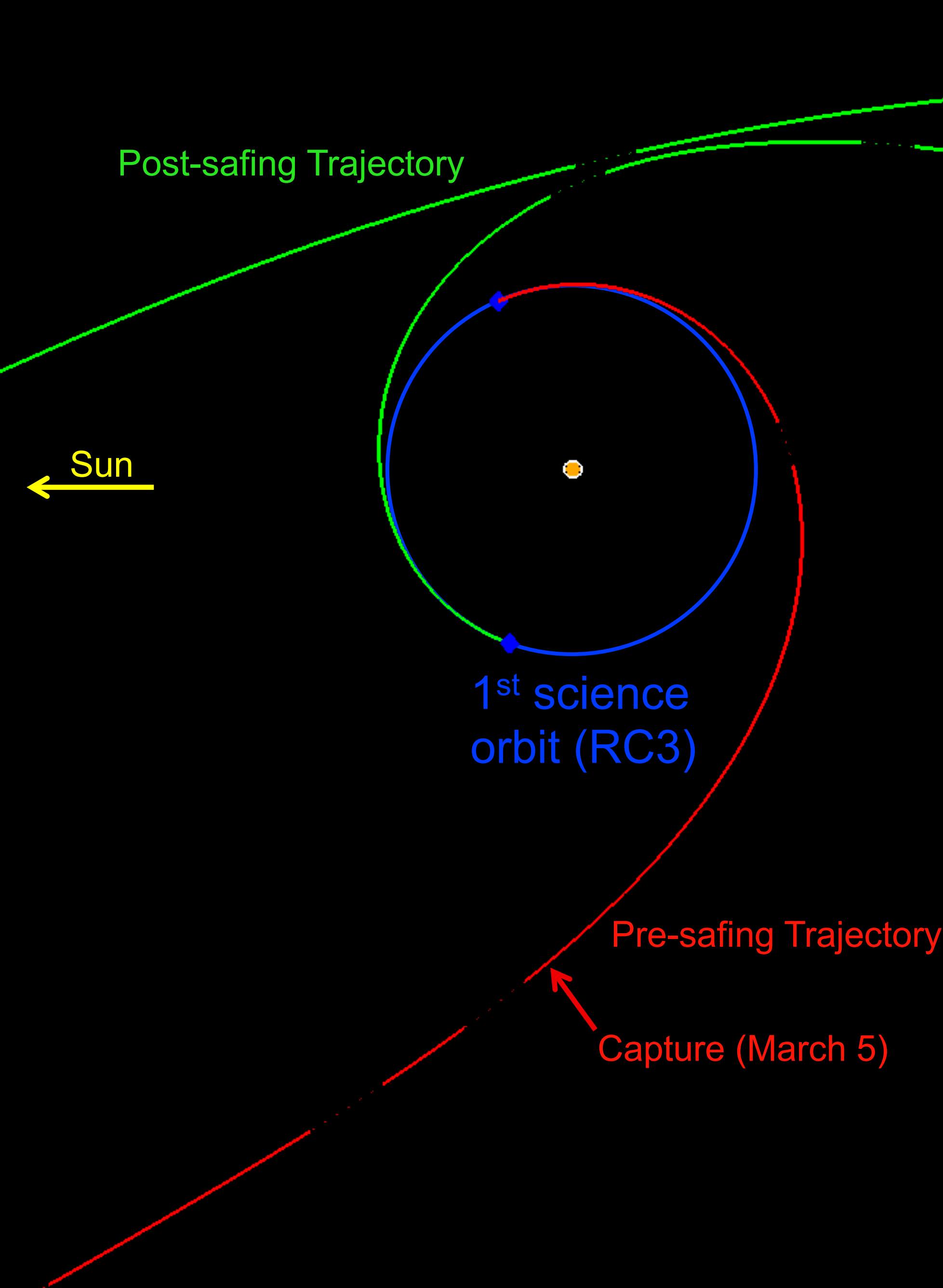
- Missed Thrust is a margin in mission design against any anomaly prohibiting thrusting for certain duration.
- Dawn usually used 28 days, but this is not the "magic number"
- Dawn's longest outage was 14 days when not under pressure and with JPL internal review. Less than 7 days when under time pressure.
- Early detection of thrust outage is critical
  - Thrust Verification (TV):
    - During thrusting, use LGA for minimum telemetry
    - To turn on transponder, thrust level was lowered
    - Tracking data available for OD
  - No Downlink Thrust Verification (NDTV):
    - During thrusting, short DSN pass to detect S/C safe mode signal
    - DSN and Comm Chief will contact in case of signal detection

Missed Thrust and Mission Delay



Dawn

Missed Thrust: Sample Case



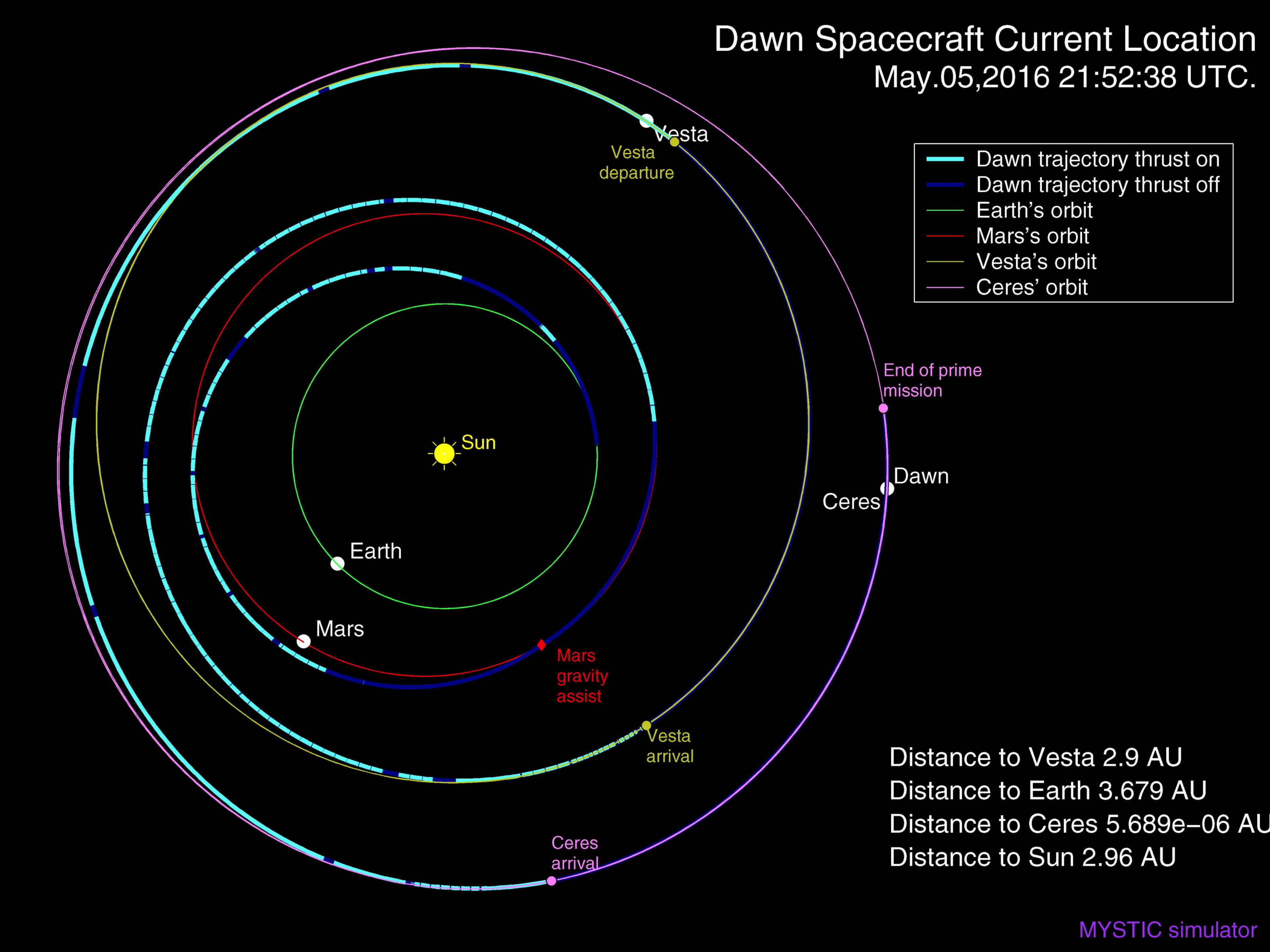
Safing during Ceres approach (Sep., 2014) changed the approach geometry and timeline

Entry to 1st Science orbit was delayed by a month.

Immediate revision of approach plan kept Dawn in nominal operational timeline

Coasting time management

- Optimal/Forced Coasting:
  - Project defines "forced coasting"
  - Mission design identifies "optimal coasting"
- Dawn was under time constraint, arriving at Ceres, and forced coasting times were tightly controlled by project.
- Once the future forced coasting is defined, it is often very difficult to change without, potentially seriously, impacting the mission design.

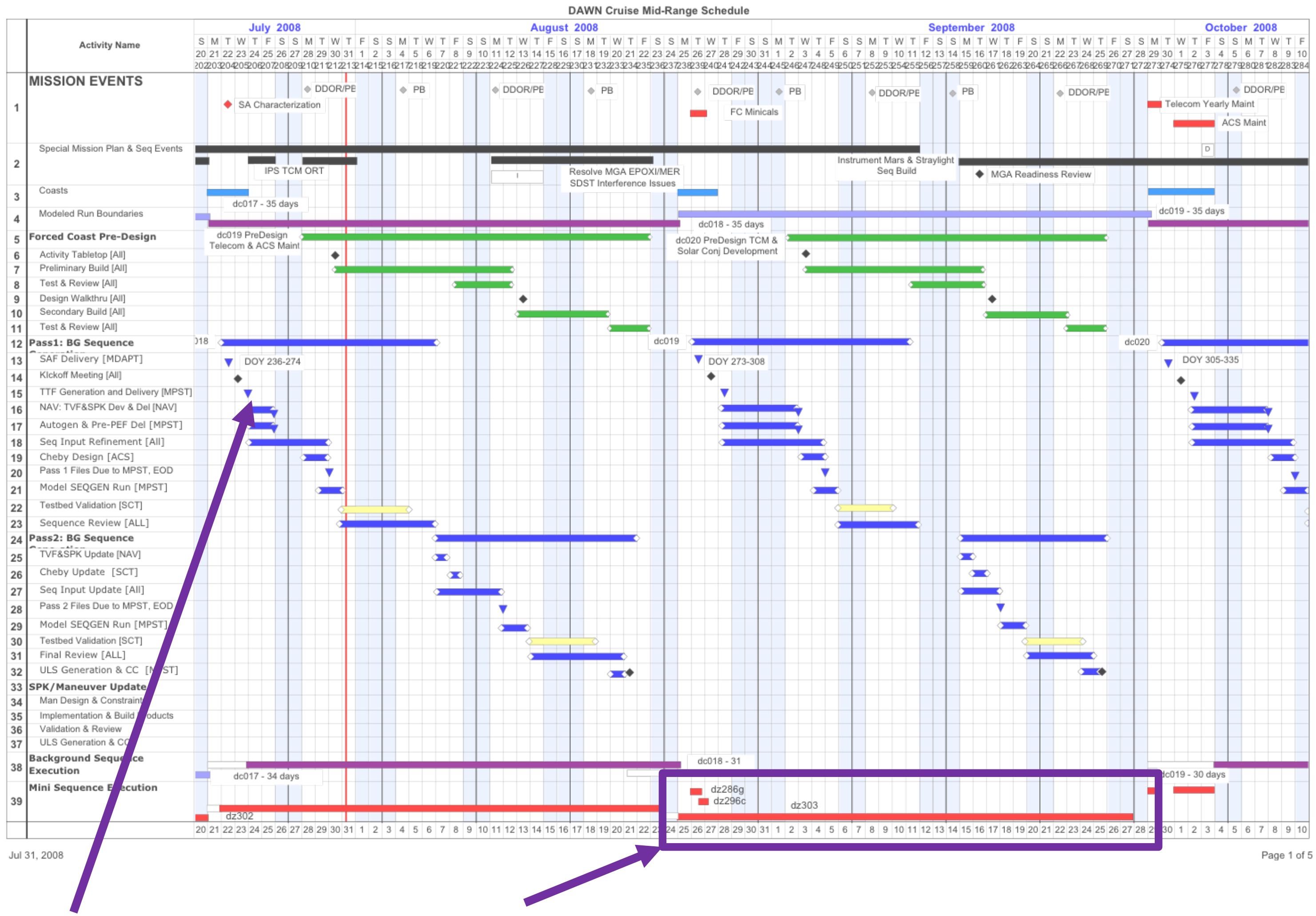

Dawn Spacecraft Current Location
May.05,2016 21:52:38 UTC.
Dawn trajectory thrust on
Dawn trajectory thrust off
Earth's orbit
Mars's orbit
Vesta's orbit
Ceres' orbit
Vesta
Vesta departure
Sun
End of prime mission
Dawn
Ceres
Earth
Mars
Mars gravity assist
Vesta arrival
Ceres arrival
Distance to Vesta 2.9 AU
Distance to Earth 3.679 AU
Distance to Ceres 5.689e−06 AU
Distance to Sun 2.96 AU
MYSTIC simulator

Orbit Determination

Dawn

- “Precision” OD neither possible nor required.
- Infrequent tracking passes during cruise and orbit transfer
  - 1 HGA per week during cruise
  - 1 HGA per month after second RWA failure
  - LGA pass is during thrusting
- Heavy usage of stochastic acceleration model
  - Polynomial Acceleration stochastics
  - Small Forces (RCS thrusting events) bias stochastics
- Modeling long IPS burn is not simple.
  - IPS thrust level changes during TV pass
  - IPS thrust vector is not constant, especially during transfers.
- Small forces response is unbalanced for outboard IPS, and balanced for central IPS.

Thrust design strategy during cruise



OD is used to build 4 weeks long thrust arc starting 4 weeks later

Dawn

Thrust modeling

- ”Long burn” model :
  - One contiguous thrust arc as one finite maneuver model
  - Use time series for throttle level changes
- “Short burn” (or piecemeal) model:
  - Model each different thrust level as separate finite maneuver model
- Estimate start, stop time, aim vector, and time series models for thrust magnitude and mass flow rate.
- *Compared against reconstruction, long burn model showed slightly better prediction.*
- *See reference (Abrahamson, 2013) for more and OD configuration.*

Thrust modeling

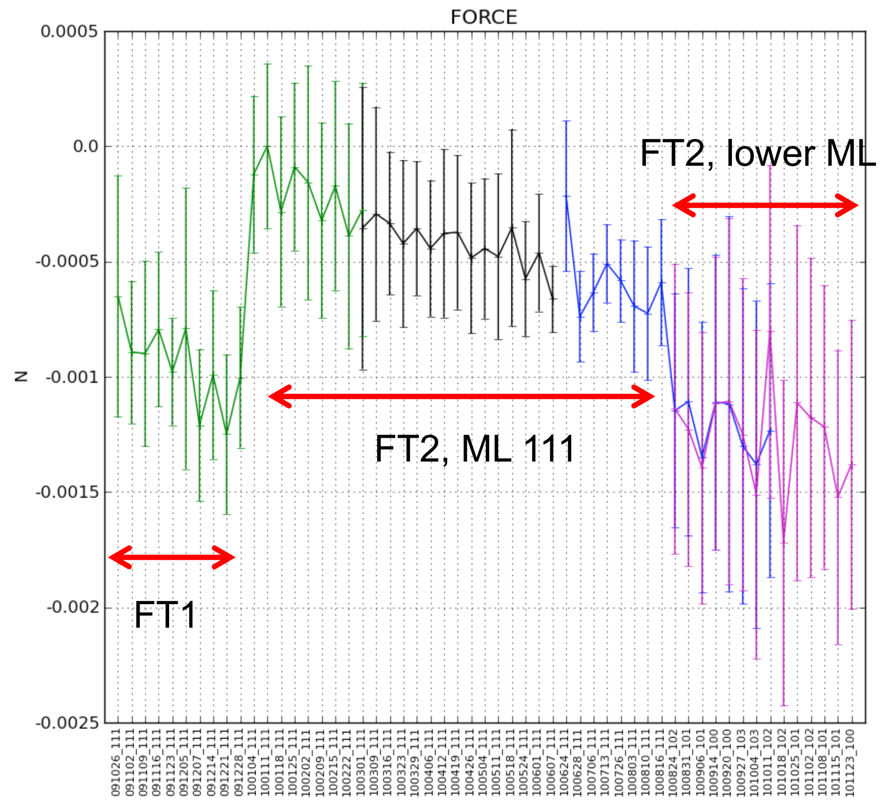
Dawn

- Telemetry data used for thrust modeling:
  - S/C bus attitude
  - IPS gimbal angles
  - IPS thrust levels (to confirm sequenced value)
- In practice, the predicted bus attitude, predicted throttle level and static gimbal angles can be assumed without compromising the solution.
- Dawn does not have accelerometer onboard.
- Momentum desaturation (WOL) records were reconstructed using RCS thruster events and used for OD.

IPS calibration

Dawn

- Dawn had two dedicated IPS calibrations after launch
  - Complete calibration of 111 thrust levels for 3 IPS thrusters are impossible. Select the most likely levels where more accurate maneuvers are required.
- Dawn OD team continued in-flight calibrations by estimating thrust magnitude and pointing.
  - Thrust magnitude adjustment to maneuver design by scale factor over throttle table
  - Pointing adjustment to ACS by aim vector update



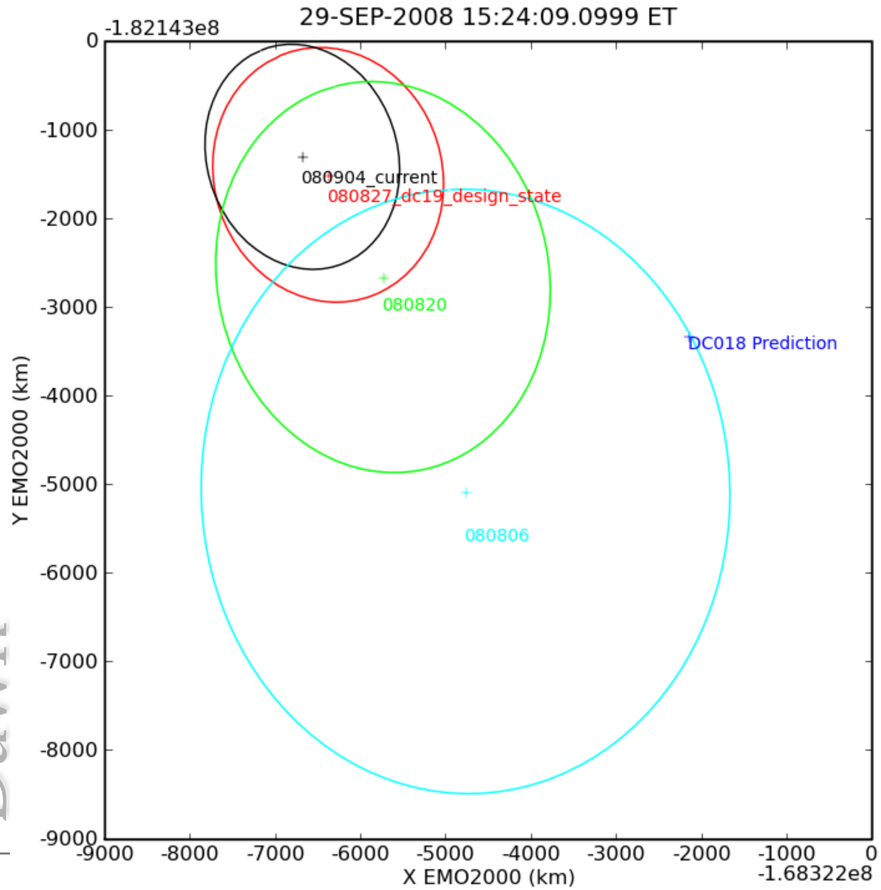
Tracking Data & Schedule during cruise

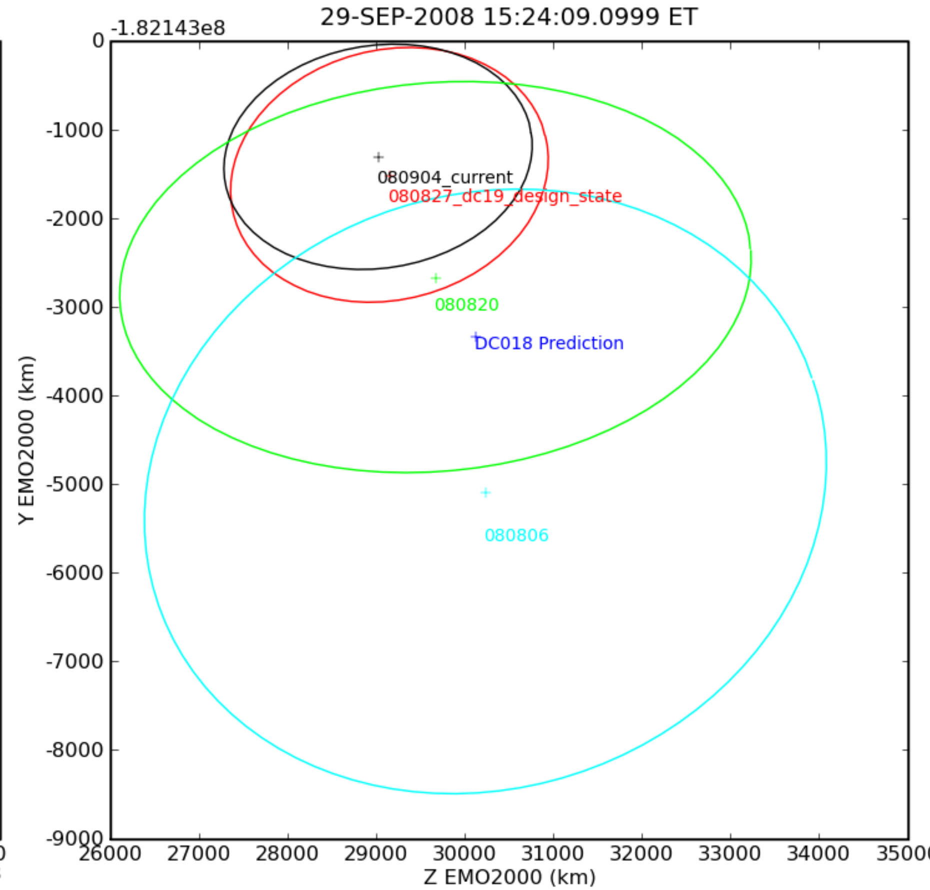
Dawn

- Cruise between Earth to Vesta:
  - Once a week HGA pass (6 hour Doppler + Range)
  - Once a week LGA pass (2 ~ 3 hour Doppler only)
  - Two DDORs per month as complementary tracking data
- Coasting around MGA;
  - Daily tracking passes with Doppler & Range
  - Two nominal TCMs before MGA
- Cruise between Vesta and Ceres (RWA turned off);
  - Once in 4 weeks HGA pass (6 hour Doppler + Range)
  - Once a week LGA pass (~4 hour Doppler only)
  - Two DDORs per month as complementary tracking data

- During HGA pass & DDOR, IPS was stopped.
- During LGA, IPS was on with thrust level was lowered to power transponder. No Ranging during LGA after certain Earth distance.

OD performance during cruise





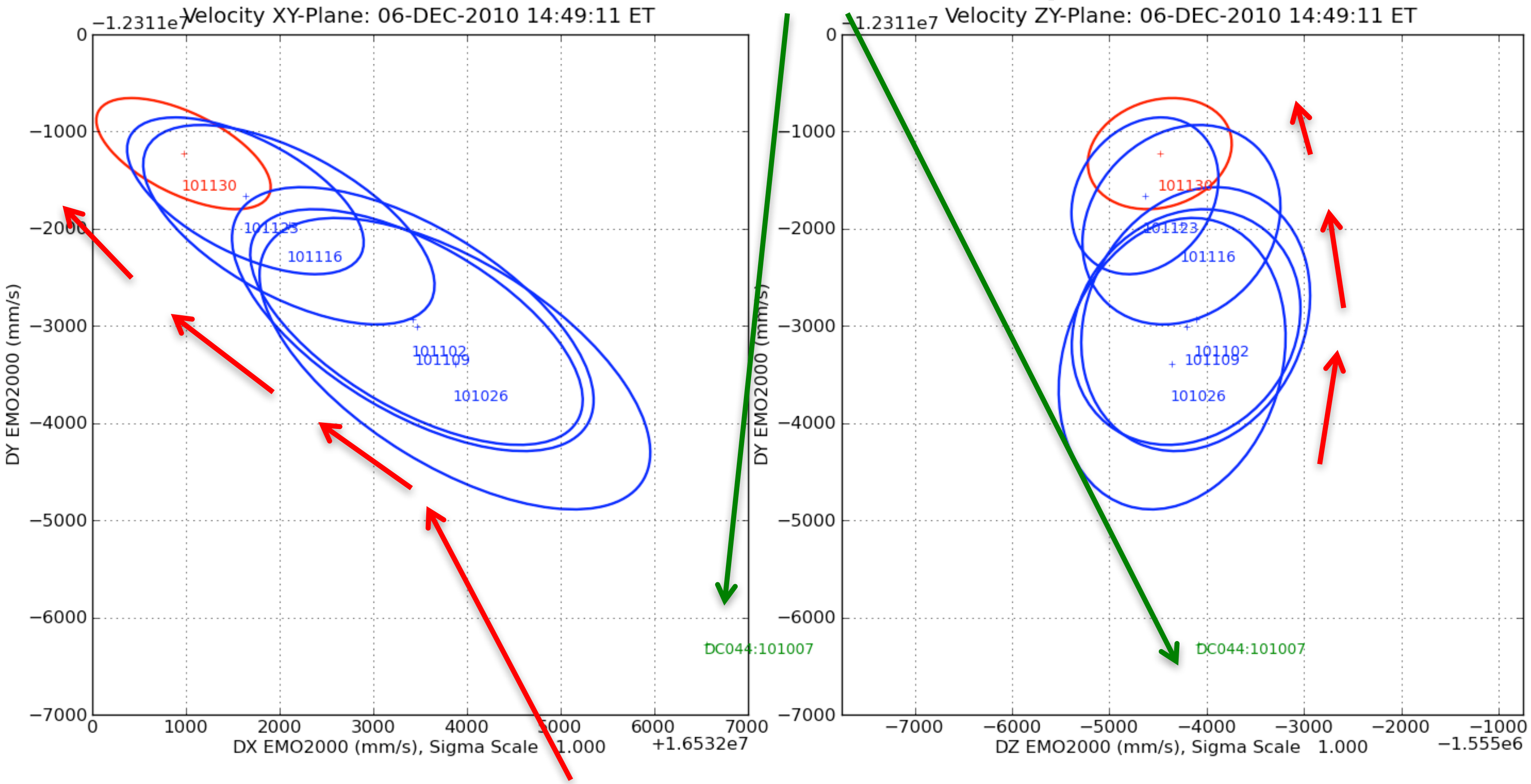
- OD in-arc reconstructions were statistically consistent at the 1-sigma level
- OD predictions were less consistent until the observed thruster output was fed forward into the predicted thrust, after which time the predictions performed at the 1-sigma level.

Dawn

OD prediction over thrusting

Dawn

We want to end up here



But, successive weeks of tracking data find us here

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Dawn

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Dawn

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The Great Learning (大學)
by Confucius

孔子

Rectify your mind (修身)

Understand your system and processes.

Regulate the family (齊家)

Work with your flight team.

Rightly govern the state (治國)

Educate your review board.

The whole kingdom is tranquil and happy! (平天下)

SEQ.	DCO	Map time	Error (km)	Error (m/s)	w/TV (km)	w/TV (m/s)	w/TV and state (km)	w/TV and state (m/s)	TV,state,SFF (km)	TV,state,SFF (m/s)
DC051	02-SEP-2012	01-OCT-2012	632.0	0.64	--	--	--	--	--	--
	“	29-OCT-2012	1970.0	1.07	2240.0	1.35	984.0	0.97	907.0	0.89
DC052	08-OCT-2012	29-OCT-2013	451.0	0.29	--	--	--	--	--	--
	“	26-NOV-2012	1090.0	0.65	1160.0	0.87	951.0	0.66	867.0	0.60
DC053	13-NOV-2012	26-NOV-2012	1450.0	0.89	--	--	--	--	--	--
	“	07-JAN-2013	3200.0	0.99	3820.0	1.45	1740.0	0.98	1750.0	1.00
DC054	03-DEC-2012	07-JAN-2013	2840.0	1.20	--	--	--	--	--	--
	“	05-FEB-2013	6050.0	1.54	6390.0	1.70	565.0	0.46	614.0	0.48
DC055	14-JAN-2012	05-FEB-2013	1430.0	1.02	--	--	--	--	--	--
	“	05-MAR-2013	4420.0	1.42	4350.0	1.38	478.0	0.44	497.0	0.45
DC056	05-FEB-2012	05-MAR-2013	358.0	0.15	--	--	--	--	--	--
	“	26-MAR-2013	1000.0	0.49	868.0	0.30	132.0	0.12	142.0	0.13
DC057	05-MAR-2013	26-MAR-2013	323.0	0.21	--	--	--	--	--	--
	“	29-APR-2013	1740.0	0.71	1220.0	0.36	329.0	0.21	351.0	0.23
DC058	09-APR-2013	29-APR-2013	281.0	0.19	--	--	--	--	--	--
	“	28-MAY-2013	962.0*	0.42*	784.0*	0.23*	80.7*	0.52*		
DC059	05-MAY-2013	28-MAY-2013	66.6*	0.03*	--	--	--	--	--	--
	“	24-JUN-2013	2430.0*	1.39*	633.0*	0.35*				